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SUMMARY

Jezioro Okrągłe IG 1 and Jezioro Okrągłe IG 2 boreholes are located in NE Poland, within the Mazury-Suwałki Elevation, which is part of the SW East European Platform. They were drilled in the NW part of the Mesoproterozoic Suwałki Massif. The Jezioro Okrągłe IG 1 borehole was drilled in 1965, and the Jezioro Okrągłe IG 2 borehole – twenty years later.

In the Jezioro Okrągłe IG 1 borehole, the top of the crystalline basement was encountered at a depth of 1064.5 m, while in the Jezioro Okrągłe IG 2 – at 1085.0 m depth. The former penetrated crystalline rocks with a thickness of 335.7 m, and the latter – 1215.0 m. The crystalline basement is overlain by Cambrian, Ordovician, Silurian, Permian, Triassic, Jurassic, Cretaceous, Paleogene and Quaternary deposits.

The rocks obtained by the drilling have been the subject of research until the present day. They include new studies, namely: petrographic, petrological, geochemical, mineralogical, radiometric, structural, petro- and palaeomagnetic, palaeontological, biostratigraphical and sedimentological.

The boundaries of chronostratigraphic units in non-cored sections of both boreholes, and in cored intervals but poorly documented biostratigraphically, are approximate. They have been determined with varying accuracy based on various criteria, such as comparison with biostratigraphically dated sections of nearby wells and regional correlations, as well as on the knowledge on the development and evolution of individual sedimentary basins in time and space.

Mesoproterozoic crystalline rocks in the Jezioro Okrągłe IG 1 borehole were encountered at a depth of 1064.5 m and the drilling was completed at 1400.2 m. This section of the Calymmian crystalline rocks is poorly variable in terms of lithology. Coarse-grained and porphyritic anorthosites dominate, with transitions into pegmatoidal anorthosites and labradorites. There are many granite veins showing features of sills. Locally, there are schlieren and ilmenite-magnetite ore nests. All these rocks are mylonitized in places to different degrees (from protomylonites to ultramylonites). The so-called damage zones with cataclasites and tectonic breccias are locally observed.Mesoproterozoic crystalline rocks in the Jezioro Okrągłe IG 2 borehole occur at a depth interval from 1085.0 (according to geophysical data) to 2300.0 m. The section is invariable lithologically and represented mainly by anorthozites with thin zones and schlieren of magnetite-ilmenite ore, and with granite veins showing features of sills (94 occurrences). Crystalline rocks from this borehole were examined microscopically in transmitted light, and analyzed for mineral composition and contents of major elements and strontium. Microscopic examinations have shown that there are many varieties among the anorthosites, for example: pyroxene, amphibole-pyroxene and myrmekite anorthozites, as well as secondarily altered anorthosites.

For the purposes of geochemical research, 246 continuous samples with a total length of over 112 m were collected from the drill core of the Jezioro Okrągłe IG 2 borehole. In the samples, contents of seven components were determined: total iron, titanium oxide, vanadium, chromium, copper, nickel and cobalt. The image visible in the scatter plots matrix for the component pairs indicates the impact of at least three factors on the distribution of the determined contents. The results of the geochemical analysis show that there are two factors responsible for nearly 97% of the total variability observed in the borehole profile. The first one, explaining 79.73% of the total variability, was associated with the phase of oxide mineralization, and the second one, explaining 17% of the total variability, with the phase of sulphide mineralization. Additionally, the third factor was considered as significant. It explains 2.3% of the total variability and is associated with local anomalous low chromium contents. This factor was related to the alkaline leaching process.

K-Ar age determinations of rocks from the Jezioro Okrągłe IG 2 borehole were carried out using the volumetric method for Ar dating and the isochrone method for interpretation. The K content was determined on quartered material. The obtained K-Ar ages range within an interval of *ca.* 1415–1465 Ma. The isochron method yielded the age of 1384 ±20 Ma. This age can be interpreted as an apparent

age corresponding to the closing time of the K-Ar system for biotite.

For the age determination of magmatic ore mineralization in the Jezioro Okrągłe IG 2 borehole, the Re-Os method was applied in 1998. It is an isotopic system that allows determining the time, origin and metalogenic history of the development of ore sulphides and oxides due to the direct dating of ore minerals in the rock. The Re-Os isochron model age for the ore samples from the Jezioro Okrągłe IG 2 and Krzemianka boreholes was 1559 ±39 Ma with the initial ratio $^{187}Os/^{188}Os$ = 1.16 ±0.06. Obtained isotopic Os data for sulphides from the Suwałki anorthosites and norites indicate their crustal source.

As a result of detailed tectonic studies, various tectonic structures were identified in both boreholes: planar (magmatic foliation S_O, metamorphic foliation S_M and composite foliation S_{O+M}, faults and fractures), linear (mineral grain lineation L_M and striae L_R), and ductile and brittle shear zones. Characteristic is the development of various mylonitic rocks that formed as a result of heterogeneous non-coaxial deformation located at various depths. In structurally examined drill cores, numerous tectonic structures were found indicating a compressional (thrusting) regime in the NW, marginal part of the Suwalki Massif. During the main deformation D_2 of highly compressional character, there was a localized development of strongly heterogeneous simple shear zones. In the Jezioro Okrągłe IG 2 borehole, there may also be so-called corner domains of intermediate kinematic nature between lateral domains and basal domains.

The lithology of ore series in the Jezioro Okrągłe area is definitely different from that of ore bodies in the Krzemianka, Udryń and Jeleniewo region. In the Jezioro Okrągłe area there are no mineralized rocks with a fine-grained and medium-grained structure and with a composition of norite, ferrodiorite and jotunite. The mineral composition and texture of Fe-Ti oxides and accompanying Fe-Cu-Ni-Co sulphides in samples from the Jezioro Okrągłe IG 2 borehole indicate their crystallization from oxide alloys, with a small amount of sulphide alloy, due to magmatic differentiation. These alloys intruded into crystallized anorthozites, forming thick ore zones and minor impregnations penetrating into the interstitial space of plagioclases. Around the zones of intense Fe-Ti mineralization, there are common manifestations of thermal alteration processes of surrounding rocks, composed mainly of plagioclases.

The mineral composition of mineralized zones in the Jezioro Okrągłe area is identical to that from the zones rich in Fe-Ti oxides, which are documented by boreholes in the area of Krzemianka and Udryń deposits. The final form of the oxide and metallic parageneses is the result of (1) intense processes of decomposition of solutions of solid, high-temperature Fe-Ti oxides and Fe-Cu-Ni-Co sulphides, (2) oxidation of ulvöspinel, and (3) continuous recrystallization of newly formed mineral phases. These processes altered the chemical composition and mineralogy of the primary magmatic oxide and sulphide parageneses. Post-magmatic recrystallization processes of oxide parageneses, induced by diffusion processes, took place at a temperature of 400°C, while the processes of alteration of mineral composition within sulphide parageneses occurred at temperatures below 160°C. The lack of norite/jotunite rocks in the Jezioro Okrągłe borehole indicates that small intrusions of alkaline rocks located in the western and/or southwestern margin of an anorthosite batholith were the likely source of oxide alloys.

The Jezioro Okragłe IG 2 borehole section comprises five documented ore-bearing zones composed of magnetite-ilmenite rocks and ore-bearing anorthosites.

Rich ore bodies, represented by magnetite-ilmenite rocks, formed as a result of injection and crystallization of oxide alloys that originated probably from small intrusions of norite/jotunite alloys, located in the SW part of the Suwałki Massif or below the present-day erosional truncation of crystalline basement rocks in the Suwałki Massif region.

The sedimentary cover in Jezioro Okrągłe IG 1 at 1064.5 m depth and in Jezioro Okrągłe IG 2 at 1085.0 m depth starts with Lower Cambrian rocks, corresponding approximately to the Terreneuvian and Series 2. The Lower Cambrian section is dominated by a fine-grained sandstone lithofacies that passes continuously into a siltstone lithofacies. The sandstones are represented by quartz arenites, and are highly porous and friable.

The Ordovician in Jezioro Okrągłe IG 1 occurs at a depth of 851.5–945.0 m. The sedimentary succession is divided into the standard global Ordovician stages from the Hirnantian through the Dapingian, which correspond in the British scheme to the Ashgilian through the Arenigian. The Ordovician deposits in the Jezioro Okrągłe IG 2 borehole occur at a depth of 860.0–968.0 m. In the depth interval of 860.0–948.4 m, the interpretation of lithology and stratigraphy is based on drill cuttings and well logs. This section is represented by the standard global Ordovician stages from the Katian through the Tremadocian (Ashgillian through the Tremadocian in the British scheme).

The Silurian section in the Jezioro Okrągłe IG 1 borehole is reduced in terms of stratigraphy and thickness (*ca.* 76.5 m). The Silurian is represented probably by the Wenlock and Llandovery here. The Ludlow and Pridoli, as well as the younger Palaeozoic deposits, have been eroded away before the Permian. In Jezioro Okrągłe IG 2, the Silurian section has not been cored.

The Silurian deposits in Jezioro Okrągłe IG 1 at 725.0 m depth and in Jezioro Okrągłe IG 2 at 735.0 m depth are overlain by Permian rocks with a thickness of *ca.* 50 m. The Permian section is represented exclusively by the Rotliegend facies assigned to the uppermost Rotliegend, *i.e.* the Pasłęka Formation of the Noteć Megacycle.

No core has been acquired from the Mesozoic succession of both boreholes. The lithology is interpreted based on well logs, drill cuttings, and correlations with nearby boreholes. The Triassic section consists only of the Lower and Middle Buntsandstein. The Lower Buntsandstein is represented by the Baltic Formation composed of claystones and mudstones with thin interbeds of limestones and sandstones. The Middle Buntsandstein is represented by the Lidzbark and Malbork formations. The major part of the Lidzbark Formation is composed of oolitic limestones. Most of the Malbork Formation consists of claystones with sandstone interbeds. The Rotliegend deposits were accumulated in a nearshore zone of a shallow basin and in an alluvial plain.

The Lower Jurassic in the Jezioro Okrągłe IG 1 borehole is 134.0 m thick, and in Jezioro Okrągłe IG 2 it attains 128.3 m. The stratigraphy of the lowermost Jurassic in both boreholes is highly uncertain. The Lower Buntsandstein claystones of both boreholes are overlain by a sandstone complex. In both boreholes, we have the Olsztyn Formation (sandstone complex) and possibly part of the Ciechocinek Formation (claystone-mudstone complex). The Middle Jurassic section is reduced and starts with Bathonian deposits. The subdivision of the Upper Jurassic has been revised in both boreholes: the Oxfordian is recognized in Jezioro Okrągłe IG 1 at a depth of 423.5–456.0 m, and in Jezioro Okrągłe IG 2 – at 437.5–466.0 m. The remaining uppermost part of the Upper Jurassic is represented by the Lower Kimmeridgian.

The Cretaceous in the Jezioro Okrągłe IG 1 and Jezioro Okrągłe IG 2 boreholes is 193.5 and 225.5 m in thickness, respectively. It is represented by the Lower Cretaceous (Upper Albian) and the Upper Cretaceous comprising the Cenomanian, Turonian (?and lowermost Coniacian) and Maastrichtian stages. The Upper Albian and Cenomanian deposits are represented by siliciclastic lithofacies. In the Turonian (? and lowermost Coniacian), carbonates are dominant: limestones and chalk. The Maastrichtian is composed of marly lithofacies. The characteristic feature of the Cretaceous sections in both boreholes is a stratigraphic gap spanning most of the Coniacian, and Santonian and Campanian.

Poorly preserved fragments of Bryozoa in the Jezioro Okrągłe IG1 borehole have been recognized in the Maastrichtian marly facies, where three taxa have been found. They belong to the order Cyclostomata represented by the two suborders Tubuliporina and Cerioporina. Among Cheilostomata (Neocheilostomatina), representatives of the families Lunulitidae and Calloporidae have been found. The richest sample in terms of biodiversity comes from a depth of 280 m, where four taxa have been identified. The occurrence of this fauna is associated with the hardground surface at the top of the ?lower Coniacian–Turonian.

In Jezioro Okrągłe IG 1, depth 300.0–330.0 m, poorly preserved faunal fragments have been found in carbonates (ranging from chalk to sandy limestones with marl interbeds) dated to the ?early Coniacian–Turonian. The bryozoan fauna from Jezioro Okrągłe IG 1 shows the greatest similarity to the faunas from Scandinavia, Denmark and the Netherlands. The presence of taxa such as *Lunulites* in Maastrichtian deposits of this borehole can be an indicator of the occurrence of favourable environmental conditions: warm waters with a basement temperature not lower than 12°C, presence of a sandy bottom, and moderate hydrodynamic regime. Colonies of Cyclostomata indicate normal salinity of the Late Cretaceous marine basin.

The Upper Cretaceous succession is overlain in both boreholes by Cenozoic deposits: at depths of 0–201.5 m in Jezioro Okrągłe IG 1, and 0–186.0 m in Jezioro Okrągłe IG 2. The Paleogene deposits are covered by the Quaternary at a depth of 183.5 m in Jezioro Okrągłe IG 1, and 166.0 m in Jezioro Okrągłe IG 2. The Quaternary deposits are represented by variously grained sands, ice-dammed lake clays and till.

Reconstruction of the burial history of Paleozoic, Mesozoic and Cenozoic deposits in the Jezioro Okrągłe IG 1 and Jezioro Okrągłe IG 2 boreholes, and of the thermal (heat flow) evolution of the basin was performed by 1-D modelling techniques using Basin Mod® 1-D software. As there are considerable stratigraphic gaps in the Paleozoic and Mesozoic sections, a few options of original thicknesses of deposits removed by erosion were tested. The assumptions included Late Caledonian uplift movements that terminated the early Paleozoic depositional phase, erosion of 500 m of Silurian deposits, Variscan movements that resulted in a removal of 1100 m of Devonian and Carboniferous deposits, and Alpine movements that reduced various Mesozoic units.

The analysis of subsidence and sediment deposition rate shows that the early Paleozoic was a period of transition from sedimentation under conditions of passive continental margin (late Ediacaran–early Cambrian) to deposition in a foredeep basin that formed due to flexural bending of the margin. This stage was characterized by a continuous increase in the tectonic subsidence rate whose peak took place in the Silurian. The sediment deposition rate in Ordovician times was low, below 10 m/Ma, but it increased in the Silurian to more than 30 m/Ma. Burial history and thermal evolution models indicate that only the accumulation of Devonian and Carboniferous deposits, with an estimated original total thickness of about 1100 m, which buried the base of the sedimentary cover to a depth of 1400–1450 m, caused a temperature increase to more than 70°C. It highly contributed to an increase in maturity of Cambrian organic matter and its entrance into an initial maturity phase of "oil window". Late Carboniferous erosion stopped the increase in burial depth and temperature. The Permian-Mesozoic stage was characterized by generally low rate and continuous deposition and a successive increase in the burial depth. However, it did not result in changes in organic matter maturity.

Interpretation of the results of Rock-Eval 6 analysis was performed on drill core fragments of Ordovician and Silurian rocks from both boreholes. Most of limestones and claystones from the Jezioro Okrągłe IG 1 borehole (Silurian and Ordovician) and from the Jezioro Okrągłe IG 2 borehole (Silurian) do not show features of source rocks, except for two thin claystone interbeds (Llandovery) exhibiting very high hydrocarbon potential. Organic matter in the Ordovician and Silurian deposits is represented most probably by type II kerogen and is thermally immature.

A separate chapter presents the results of laboratory measurements of bulk density, performed on samples taken from drill cores of both boreholes. Averaged results of the measurements are summarized in tabular form in compilation with the stratigraphic section and, for the crystalline basement (Mesoproterozoic), additionally with the lithology.

Both boreholes are covered by a similar range of well logs: gamma ray, neutron-gamma ray, gamma-gamma ray, resistivity, spontaneous potential, caliper and curvature. In the Jezioro Okrągłe IG 2 borehole, the well logs were run separately for two measurement intervals (sedimentary cover and Precambrian basement). In both boreholes, due to the lack of drill core in most of the sedimentary cover, the main source of information on lithology was the interpretation of well logs correlated with data from nearby boreholes. In crystalline rocks, gamma-gamma ray, magnetic, and spontaneous potential logging has allowed identification of individual beds with an increased content of ore minerals. Clear positive anomalies on the gamma ray curve are due to the occurrence of intensely fractured granite. Both boreholes are located in a zone of Poland's lowest heat flow density and stabilized temperature at a depth of 2000 m b.g.l., which is 40°C.

Petro- and palaeomagnetic studies in the Jezioro Okrągłe IG 1 borehole were performed on the Lower Silurian and Ordovician carbonates. Predominance of hematite is manifested in samples of rocks older than the Upper Llandeilian. Thermal analyses point to magnetite as the magnetic remanence carrier in the Ashgillian and Caradocian samples.

No physicochemical tests of formation waters have been performed in the Jezioro Okrągłe IG 1 and Jezioro Okrągłe IG 2 boreholes. In Jezioro Okrągłe IG 1 tests were performed on six water-bearing horizons. Brine inflow was reported from the Lower Triassic horizon at a depth of 710.0 m and the Lower Cambrian horizon at a depth of 960.0 m.

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